The new DGZfP Specification B12 "Corrosion Monitoring of Reinforced Concrete Structures"

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ABSTRACT: The corrosion of steel in reinforced concrete structures is one of the main threats to their durability. Based on the scientific achievements of the past decades, the knowledge about deterioration mechanisms and possible repair strategies for corrosion induced damages have found their way into practice.
Nevertheless, no standards or guidelines concerning corrosion monitoring are available in Germany today. In order to make corrosion monitoring accessible to the engineer planning repair measures of corrosion damaged concrete structures, the new DGZfP-Specification B12 was developed by the DGZfP-subcommittee "Corrosion Detection" consisting of corrosion specialists originating from planning offices, universities and companies from Germany, Switzerland and Austria. The specification was published in spring 2018.
This paper presents the new specification by highlighting its structure as well as its intended fields of application.

1 INTRODUCTION

1.1 Background

The penetration of chlorides into concrete components and the associated risk of chloride-induced corrosion of the reinforcing steel or prestressing tendons poses a great damage potential for infrastructure and marine structures such as bridges, tunnels and multi-storey car parks. This is particularly the case for the large number of constructions erected in the 1960s and 1970s, as concrete covers at that time were comparatively small and for many of these structures the chloride ions have now reached critical concentrations at the reinforcement level after about 50 to 60 years of exposure.

The rehabilitation of such constructions is often associated with demanding planning efforts, time and material-consuming repair measures which tend to be very expensive, see figure 1. In many cases this situation could have been prevented by an early detection of the corrosion risk and by taking appropriate countermeasures.

Figure 1. extensive concrete replacement of a slab (left) and a column in a parking garage due to chloride-induced reinforcement corrosion (right) (source: instakorr)

Today, it is common practice that non-destructive test methods are used to assess the corrosion risk by means of mobile, surface-bound sensors. However, these methods have their systemic limitations due to their one-time use. In order to gain additional information on the condition development with time, the time dependent acquisition of relevant corrosion parameters, a.k.a. “corrosion monitoring”, has developed into a useful supplement to traditional inspections. In this context, the expression “corrosion monitoring” is associated with test methods using built-in sensors connected to a permanently or periodically working data acquisition system.

1.2 Fields of Application for Corrosion Monitoring

One major field of application for corrosion monitoring is new structures with a limited or non-existent accessibility after completion, e.g. the outer side of tunnel shells, foundation components in chloride-containing soil, bridge decks, bearings and piers. In addition to these examples, corrosion monitoring can also be beneficial in the case of structural components which are protected by non-conductive polymeric layers such as parking decks or marine structures and for which a surface-bound acquisition of corrosion parameters (e.g. potential mapping) is impossible.

In combination with traditional inspection methods, corrosion monitoring can reduce the use of invasive probe sampling such as powder sampling for subsequent chloride analysis. In addition, corrosion monitoring provides the unique possibility to monitor the critical chloride ingress into the concrete cover, thus enabling the person in charge to initiate countermeasures before chlorides have reached the reinforcement.

However, the application of corrosion monitoring is not limited to new structures. Looking at existing structures, which represent the main part of the building stock, corrosion monitoring can also be used in cases where corrosion has already been initiated. An example is the tracking of the corrosion process in the aftermath of conducted repair measures aiming at the increase of the concrete resistivity according to repair principle “IR” in DIN EN 1504-9:2008-11 or repair principle “W-Cl” in DAfStb (2001), see Keßler et al. (2017), Hiemer et al. (2018). Another interesting field of application is the repair of cracks in concrete subjected to a short-time chloride exposure. Since it is uncertain that a crack injection will completely stop reinforcement corrosion if the chloride-containing concrete is not removed, it is recommended to use corrosion monitoring to evaluate the impact of this repair measure on the corrosion process, see Kosalla et al. (2013).

Finally, it can be stated that corrosion monitoring has been established as an integral component of repair measures featuring cathodic protection systems according to DIN EN ISO 12696: 2017-05 as it allows to check the effectiveness of the system in a simple way.

2 STATE OF THE ART IN CORRSION MONITORING

2.1 Background

For most of the commonly used inspection methods, specifications and guidelines exist which define fields of application, systemic restrictions as well as examination procedures. With this it is possible to perform structural assessments in a standardized way ensuring a high level of quality of the obtained data. In contrast to that, for corrosion monitoring there are no specifications or guidelines available so far. This is quite unusual, as the use of corrosion monitoring is explicitly required in the still valid DAfStb-Guideline "Schutz und Instandsetzung von Betonbauteilen" dating back to 2001, DAfStb (2001). As a consequence, corrosion monitoring was, until now, mainly used by a small group of specialists with a scientific background.

2.2 The new DGZfP-Specification B12 "Corrosion Monitoring"

In order to make corrosion monitoring accessible to a larger community of engineers, the new DGZfP-Specification B12 was developed by the DGZfP-subcommittee "Corrosion Detection" consisting of corrosion specialists originating from planning offices, universities and companies from Germany, Switzerland and Austria. The specification was published in spring 2018.

During the past decades, different measurement principles for corrosion monitoring have been developed. In its first chapters the specification describes the most commonly used measurement principles, their functionality, systemic limitations, typical measurement set-ups and handling and data evaluation. Thus, a compact overview of measurement principles is available to the planning engineer.

In a second step both the application of corrosion monitoring for new structures and for existing structures with an ongoing corrosion process is illustrated. By means of case studies, recommend-dations for the selection of measurement principles, possible system set-ups and sensor locations are given. In addition, examples for possible planning procedures and data evaluation are highlighted. However, the authors consciously decided not to present detailed handling instructions in this specification as the topic is considered to be too complex to be described in the necessary brevity. The detailed planning and data evaluation need to be done by a specialized planning engineer with expert knowledge in the field of corrosion and corrosion protection.

In the following chapters a brief introduction into common measurement principles as well as a selection of corrosion monitoring applications are given.

3 MEASUREMENT PRINCIPLES

3.1 Fundamentals of Steel Corrosion in Concrete

The occurrence of steel corrosion in concrete can be roughly described by four sub-processes which need to be possible simultaneously. These processes read as follows: a) anodic oxidation reaction, i.e. iron dissolution, b) electric charge transfer through the rebar, c) cathodic reduction reaction, i.e. oxygen reduction, d) ionic charge transfer in the pore solution, see figure 2.

For most concrete members subjected to North European climate sub-process b to d are possible. The protective properties of the cementitious matrix embedding the reinforcement stems from its high alkalinity with pH values of 12.5 and higher. In such a milieu steel develops a protective oxide layer, better known as the passive layer, which almost entirely obstructs the anodic steel dissolution (sub-process a). Under practical conditions there are two main mechanisms causing the breakdown of this protective passive layer:

- the large scale breakdown of the passive layer due to chemical reactions of alkaline components of the concrete with carbon dioxide (carbonation) resulting in a distinct drop of the pH value down to 9 (“carbonation induced reinforcement corrosion”),
- a local breakdown of the passive layer once the concentration of chlorides (from deicing salts or sea water) at reinforcement level exceeds a critical chloride threshold value (“chloride induced reinforcement corrosion”).

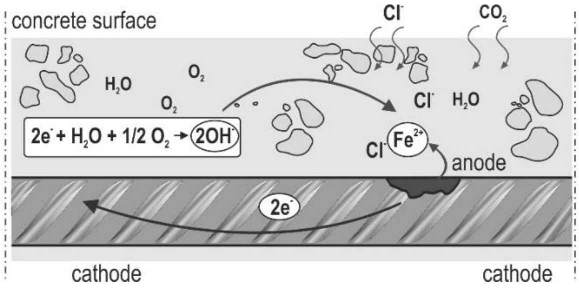

Figure 2. Schematic of chloride induced reinforcement corrosion.

Chloride induced corrosion is the most common field of application for corrosion monitoring.

The life span of a concrete member subjected to a chloride attack can be divided into the time before corrosion initiation (“initiation phase”), and the time after corrosion initiation (“deterioration phase”). During the initiation phase chlorides penetrate into the concrete. Once the chloride concentration at rebar level exceeds a critical concentration, the first local breakdown of the passive layer marks the transition from initiation phase to deterioration phase. As the potential of corroding steel electrodes in concrete is significantly lower than that one of passive steel, corrosion initiation goes along with a distinct drop of the reinforcement potential in that region.

3.2 Measurement Principles – an Overview

The most common measurement principles for the monitoring of reinforcement corrosion are the recording of electrochemical potentials, currents and the concrete resistivity.

Due to the interrelation between corrosion state and potential, the transition from initiation phase to corrosion phase can be detected by monitoring the potential differences between the reinforcement and embedded reference-electrodes (most common: MnO_2-electrodes).

Time-dependent changes of the corrosion current between anodic and cathodic surfaces are also a good indicator for changes in corrosion activity. However, current measurements require an electric separation of anodic and cathodic regions. For existing structures this can be achieved by locating suspected anodic reinforcement regions and isolating them by means of cutting or core drilling (Mayer et al. (2018)) on site. As an alternative so called “substitute anodes” can be embedded in regions with an increased risk of corrosion initiation.

Monitoring the electric resistivity of the concrete (“concrete resistivity” hereafter) may also add valuable information for the evaluation of corrosion activities or risks, as the electrolytic charge transfer in the concrete is strongly governed by its resistance. Concrete resistivity measurements can also be used as an indicator for a possible chloride ingress as chlorides enter the concrete being dissolved in water. Resistivity measurements can be used e.g. to monitor the functionality of a sealing, as water ingress will lead to a distinct drop of concrete resistivity (Sodeikat (2010)).

Additional monitoring principles like linear polarization resistance measurements etc. are also covered in the specification, but will not be presented in this paper.

4 CORROSION MONITORING DURING THE INITIATION PHASE

4.1 Background

Corrosion monitoring during the initiation phase is primarily used to monitor the ingress of the depassivation front. This kind of monitoring is convenient for new constructions or for repair measures during which the chloride-containing concrete cover is fully replaced.

For corrosion monitoring during the initiation phase, sensor systems have been developed which allow to track the penetration of the depassivation front with time. Electrochemical measurements (like potential, corrosion current and linear polarization resistance measurement) are performed by means of a depth-staggered arrangement of sensor components between the concrete surface and the reinforcement (a1 to a6 (figure 3)). If the exact sensor position is known, the depassivation time of the reinforcement can be estimated based on the latest measured results. In conjunction with models for durability assessment, corrosion monitoring during the initiation phase can be used to calibrate prediction results and to improve their accuracy, Mayer (2009), Sodeikat (2006).

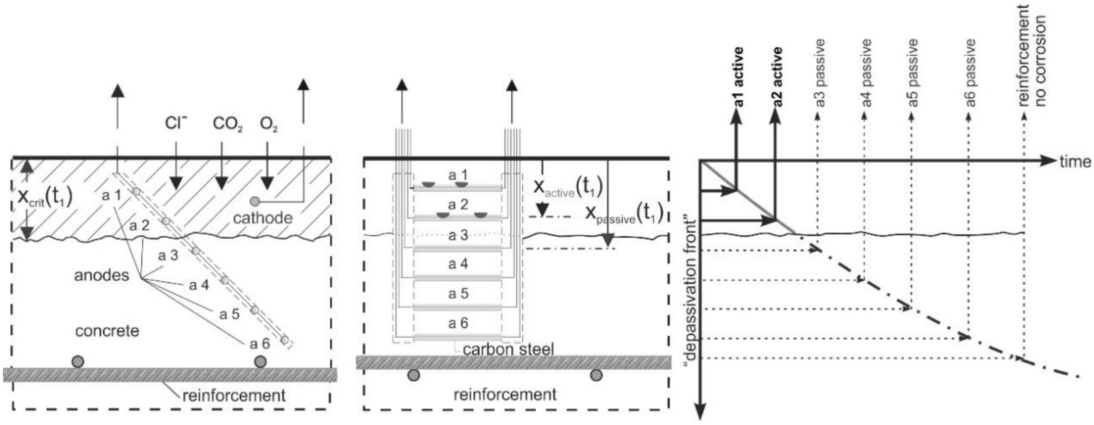

Figure 3: Depth staggered sensor arrangement for predicting the depassivation time of the reinforcement

4.2 Case Study: Multi-Storey Car Park with Partial Surface Coating

The multi-storey car park treated in this practical example was completed in 2006, see Mayer et al. (2009). The floor slabs were designed as a continuous system with centric prestressing. The prestressing and the structural design of the top side are intended to exclude load-related cracking in the field area. Support areas in which crack formation on the upper side had to be expected were provided with a crack-bridging surface protection system according to RL-SIB 2001, see DAfStb (2001). In field areas in which the upper side is permanently under compression considering all load combinations, the application of a surface protection system was dispensed. Instead, a proof of durability against chloride-induced corrosion was provided by means of a fully probabilistic service life design in combination with a maintenance plan which prescribes an annual inspection of the parking deck surfaces for crack formation and a treatment of newly occurring cracks. To observe the chloride ingress into the uncoated structural concrete, a corrosion monitoring system consisting of 25 corrosion sensors of the so called anode-ladder-type (Sensortec GmbH) were installed, see figure 4, left. These corrosion sensors were distributed in the driving lanes as well as in parking spaces. The sensor arrangement was based on the highest expected chloride exposure on the access level and on the parking levels. In this specific car park, short term parking was expected. Therefore, it was impossible to predict whether this will result in a higher chloride load in the parking areas or in the lane areas.

The sensors were mounted on the upper reinforcement layer before casting the slabs. The sensor inclination was adjusted so that the top rung had a scheduled concrete cover of approximately 15 mm. After casting was completed, a functional test was carried out and the concrete cover of the top rung of each anode ladder was determined by non-destructive measurements.

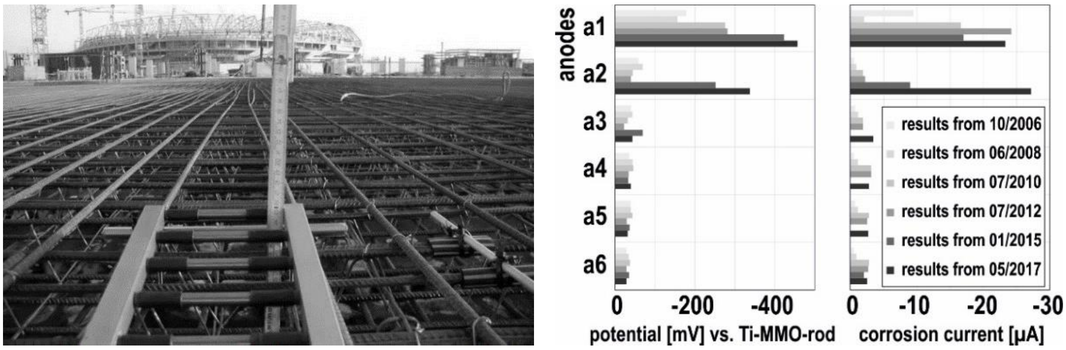

Figure 4: Installation of an "anode-ladder" corrosion sensor on the upper reinforcement layer (left) and time-dependent development of potential and corrosion currents of an anode ladder showing corrosion initiation of the first (a1 in 2010) and second (a2 in 2015) anode rung (right)

As part of the regular sensor readings, the potential of each anode rung was measured against a mixed metal oxide coated titanium (Ti/MMO) bar which was embedded near to the anode ladder. In addition, the corrosion current between the Ti/MMO and each anode rung was measured ten seconds after short-circuiting and the AC resistance between two adjacent anode rungs was recorded. The corrosion initiation on an anode rung can be recognized as a clear drop in potential and an increase in corrosion current. An example for a corrosion initiation at an anode rung is shown in figure 4, right. During the measurement in 2010 a significant decrease of the potential and a corresponding increase of the corrosion current was detected at the anode rung a1, the other anode rungs are passive at this time. In 2015, a significant drop in potential and an increase in corrosion current was measured on the second anode rung a2, the corrosion current increased in the subsequent measurement in 2017, while the anode rungs a3 to a6 will remain passive.

The results obtained with the corrosion monitoring system show that the actual chloride penetration front in non-cracked concrete is still well below the pre-calculated penetration front of the design stage.

5 CORROSION MONITORING DURING THE DETERIORATION PHASE

5.1 Background

Corrosion monitoring during the deterioration phase, i.e. after the depassivation of the reinforcement, is mainly used to assess time-dependent changes in corrosion activity after repair measures. For this purpose, corrosion current measurements of corroding reinforcement sections (anode) against a defined cathodic electrode versus time are particularly suitable as a measuring principle, often in combination with polarization resistance measurements, potential measure-ments and measurements of the concrete resistivity.

As shown in the case study, a depth-staggered sensor arrangement is essential for forecasting the initiation time of corrosion. In contrast, when performing corrosion monitoring of existing struc-tures, the relevant corrosion parameters should be determined in the present corrosion system, without significantly changing the boundary conditions. If possible, no additional anodes should be introduced, but the measurements should be carried out on the existing reinforcement. Therefore, depassivated sections of the reinforcement (anodes) can be isolated and measured against the remaining passive reinforcement (cathode). If no suitable passive reinforcement sections can be found, it is also possible to use subsequently embedded cathodes.

It has to be noted, that corrosion monitoring in the corrosion state allows for quantitative or semi-quantitative statements on the change of corrosion activity. On the other hand, it is generally NOT possible to get reliable information about the actual cross-sectional loss of the rebar. This applies in particular for chloride induced pitting corrosion of steel in concrete.

5.2 Research application: Corrosion Monitoring on coated concrete specimens according to repair principle "IR" in DIN EN 1504-9:2008-11

In a cooperative research, funded by the German Research Foundation and carried out by the Munich University of Applied Science and Technical University of Kaiserslautern, fundamental questions concerning the repair principle "IR" were the subject of research. This repair principle is subject of controversy and the key question was by what means it is possible to increase the resistivity of the concrete in order to reduce the corrosion activity of steel in chloride containing concrete to a negligible level. Therefore, two-parted test specimens were produced. The upper part consists of chloride-containing concrete with two anodes and depth staggered stainless steel rods to allow for the measurement of depth staggered concrete resistivities as well as corrosion currents and potentials against a corrosion resistant steel rod, which serves as cathode and reference electrode at the same time. In the lower, chloride free part of the test specimens, black steel anodes were placed in a depth staggered way in order to study a possible corrosion onset due to migrating chlorides from the upper to the lower part of the test specimen, see figure 5.

Three different coatings, a OS 4 and a OS 8 coating system according to RL-SIB as well as a single layered coating based on Polyurethane were applied in order to study their effect on the dehydration of the concrete. After application of the coatings the test specimens were stored in a climate chamber featuring 22°C and 55 % relative humidity (r.h. hereafter).

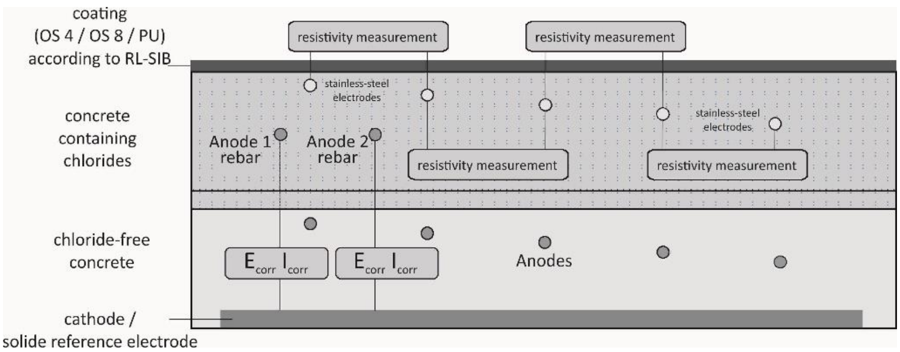

Figure 5: Test specimen with a depth staggered arrangement stainless steel electrodes and black steel anodes which allow for measuring corrosion currents (I_{corr}), potentials (E_{corr}) and concrete resistivities

The change of concrete resistivity with time of one coated (OS8) and one uncoated (Ref) specimen with concrete containing chloride is shown in figure 6, left. A significant increase in concrete resistivity of the uncoated sample within the first 10 months of conditioning by a factor of 40 can be determined. The dehydration of the sample coated with OS8 is significantly slower and reduced (factor of 1.8) compared to the uncoated specimen. The measured corrosion currents are shown in figure 6, right. In the case of the uncoated test specimens, a decrease in corrosion current within 15 months by a factor of approx. 2000 in the case of conditioning in dry climate (55% r.h.), while exposure to damp conditions (98% r.h.) does not lead to any reduction in corrosion currents. The test specimens, which are coated with a system open to diffusion (OS4), have a similar decrease in corrosion currents with dry storage climate as the uncoated test specimens with the same climate. On the other hand, the test specimen coated with almost impermeable OS 8 and PU show a slower and lower decrease in corrosion current (Factor 7).

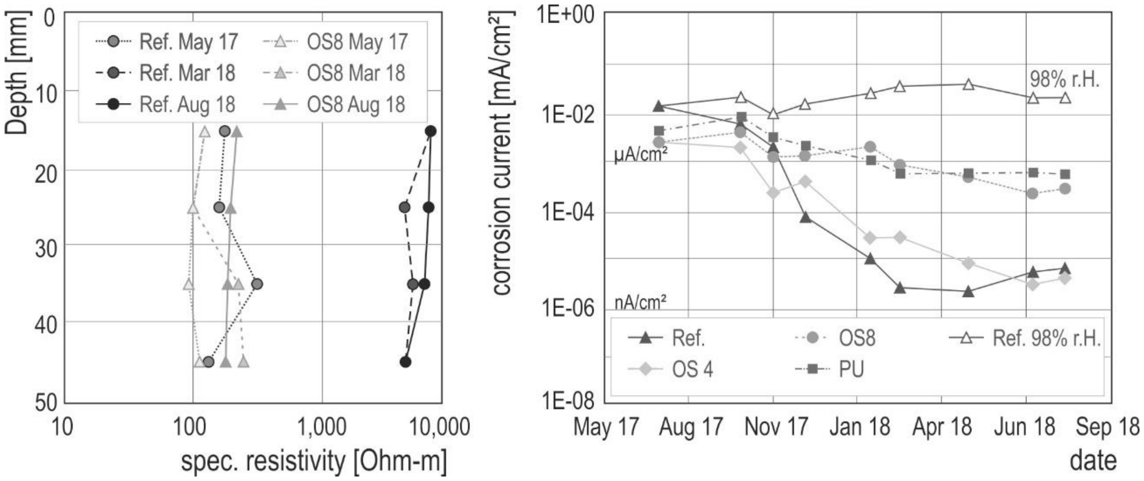

Figure 6: Depth-staggered concrete resistivities of a coated (OS8) and an uncoated test specimen (Ref.); right: corrosion currents of coated specimens exposed to 55 and 98 % r.H.

6 CONCLUDING REMARKS

Since Spring 2018 the new DGZfP Specification B12 "Corrosion Monitoring of Reinforced Concrete Structures" is available filling a long-existing gap in the German set of rules concerning repair measures on reinforced concrete structures. With this specification at hand, the planning engineer has access to basic information about the components, the planning and application of the most commonly used corrosion monitoring principles and equipment. The authors believe that this specification is an important step forward towards the implementation of corrosion monitoring as a standard option for repair strategies for reinforced concrete structures.

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